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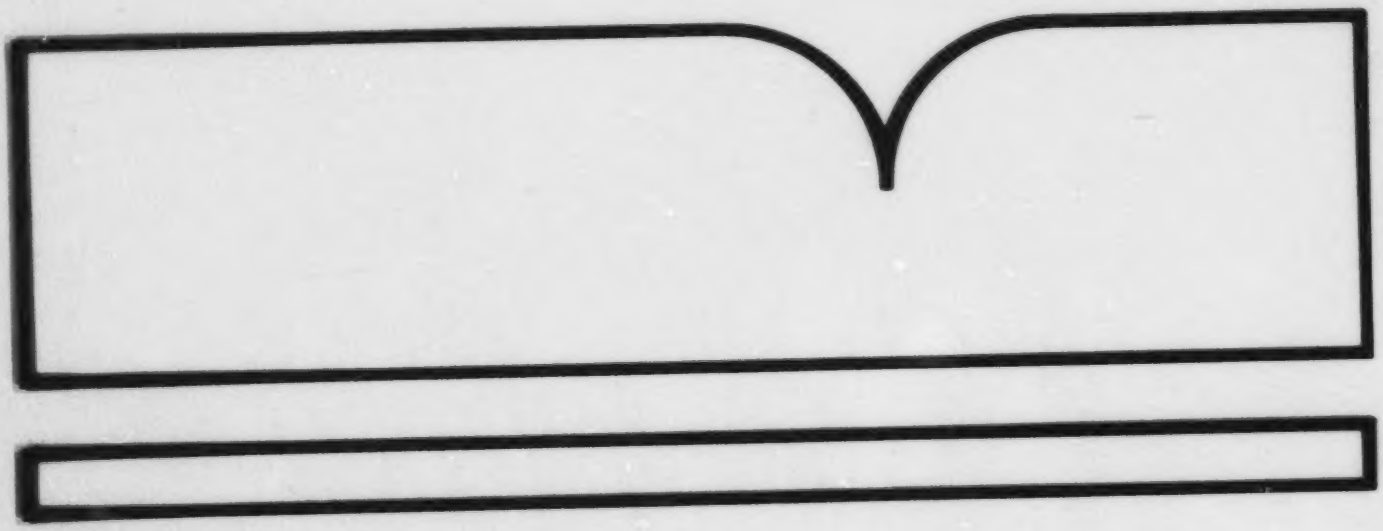

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EVALUATION OF ANAEROBIC, EXPANDED-BED CONTACTORS FOR MUNICIPAL WASTEWATER TREATMENT

by

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16. ABSTRACT

The anaerobic expanded-bed contactors for treating dilute municipal wastes were evaluated. A 334-liter diatomaceous earth, a 334 liter granular activated carbon, a set of two 66-liter sand, and two 3-liter diatomaceous earth reactor systems were used. For the most part the feed was Cincinnati Mill Creek Plant primary effluent which has a rather high industrial component and high sulfate content. Three liter laboratory reactors were fed with synthetic wastewater only.

In pilot scale experiments total COD removals up to 75% were obtained, although average removals for the three systems investigated were somewhat less. However, this performance may not be representative of the anaerobic expanded bed contactors. It is believed that the presence of sulfate reducing bacteria adversely affected methanogenesis. Consistently better results were obtained in the laboratory scale experiments conducted with synthetic wastewater which did not contain excess sulfate. The level of sulfate to COD ratio which adversely effects the anaerobic process is being investigated. Reporting the data in BOD would also result in BOD removal efficiencies which will be higher than the COD removal efficiencies reported in this paper.

In the early part of the research plugging problems occurred in the graded gravel underdrains. Design of systems which will not plug will be a major challenge for designers of full-scale reactors. As the design of the reactors improved the anaerobic expanded-bed system may prove to be a viable alternative for treating municipal sewage.

17. KEY WORDS AND DOCUMENT ANALYSIS

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EVALUATION OF ANAEROBIC, EXPANDED-BED CONTACTORS FOR MUNICIPAL WASTEWATER TREATMENT

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INTRODUCTION

The evaluation and applicability of anaerobic processes for wastewater treatment has received considerable attention for the last three decades. However most of the applications have been on high strength wastes. Various industrial wastes have been treated successfully by single-stage anaerobic digestors, and the success of the contact process was mainly attributed to the uniform mixing of the organisms and substrates and their recycling. Application of the contact process in various different situations led to the belief that anaerobic treatment

becomes more economical than aerobic treatment only when the strength of the waste is greater than 4000 mg/l COD, which was concluded by Cillie et. al. (1).

Following this, various bench-scale and pilot plant studies were conducted to further evaluate the possible application of anaerobic treatment processes for treating low-strength wastes. Simpson (2) investigated a pilot study on a contact digestor for treating dilute urban wastes, from which he concluded that the contact process does offer an alternative to conventional treatment of domestic sewage. At a temperature of 22°C digestor failure occured when a loading of 80 g BOD or 280 g COD per kg VSS per day was exceeded: BOD reductions of 80% were recorded when the loading was 0.04 lb BOD/cu.ft./day and the retention time 12 hours.

During the early 1970's a number of research efforts were directed towards innovating the anaerobic treatment and finding ways to achieve high concentrations of effective biomass in anaerobic reactors, so that the hydraulic retention time of the reactors could be decreased. Various studies conducted on biological denitrification processes showed encouraging results. Smith et. al. (3) reported pilot studies of downflow, fixed film reactors with biomass concentrations ranging from 7275 to 21400 mg/l VSS and contact times of 5 to 15 minutes for achieving 90% nitrate removal. Jeris (4) reported studies on upflow, expanded denitrification columns which gave 99% nitrate removal for detention times of 6.5 minutes and at surface loadings of 15 gpm/sq. ft.

The concept of manipulating sensitive bacteria to grow on a static surface was introduced by Young and McCarty (5). Their upflow filters enabled high biomass retention at short hydraulic retention times. A progessive development from attached microbial films in trickling filters, was its application in anaerobic processes. Jewell and MacKenzie (6) demonstrated accumulations of up to 10 times the mass per unit volume in static attached films over suspended microbial systems.

The studies on the anaerobic filters by Young and McCarty (5) and other subsequent investigations gave excellent results as they combined high loading capacity with high efficiency and eliminated external sludge separation. Parallel experiments on anaerobic sludge bed reactors using expanded and fluidized beds also showed promising results. Frostell (7) did a comparative study of anaerobic filters and the sludge bed system and reported no significant difference in the performance of the two

systems as regards COD reduction and gas production at various loadings. Though the anaerobic filter was marginally superior, this study clearly showed that good sludge retention could be achieved in a sludge bed reactor coupled with an external sludge separation system. Some of the other marginal benefits of the sludge bed system were that it would be an economically attractive alternative to the anaerobic filter in light of the performance in Frostell's study. Excellent sedimentation is achievable because of the active degasification of sludge flocs by gas-stirring.

The application of anaerobic, expanded bed, up-flow reactors for treating dilute urban wastes has been studied by Jewell et. al. (8) and others for several years. Jewell et. al. (8) concluded from their study in which they tested the anaerobic attached film expanded bed (AAFEB) system for a 200 day continuous feed period, that it successfully treated primary settled domestic waste waters at 20°C. With hydraulic retention times less than 30 minutes, most of the biodegradable organics were removed and the effluent had less than 40 mg/l COD and 5 mg/l suspended solids. Maximum organic removal efficiencies occurred up to an organic loading of 4 kg/cu m. per day. The AAFEB process was not affected by instantaneous fluctuations in temperature, organic concentrations and loading rate and could be operated at retention periods two to three orders of magnitude shorter than most other anaerobic processes.

OBJECTIVES

The project was initiated in 1980 when construction grant funding of a fullscale municipal wastewater treatment plant under the Innovative and Alternative (I&A) Technology program was requested. The US EPA staff performing the I&A review determined that sufficient data were not available to justify funding the project. The original objective of the research was, therefore to determine if the process would meet conventional secondary effluent limitations. When two years of experimentation with 3 pilot scale reactors did not produce an effluent of expected quality, the project was reviewed for possible explanation for the differences. Among others, sulfate reduction was considered as a possible reason for limited methane production and organic matter degradation. In anaerobic systems the sulfate can serve as a terminal electron acceptor in biologically mediated reactions. It is known that methanogenesis in natural

ecosystems does not occur when sulfate is present, as the conversion of acetate to CO_2 with sulfate reduction is thermodynamically more favorable than acetate conversion to CO_2 and CH_4 (9, 10, 11, 12, 13). With wastewaters containing influent COD's of 200 to 250 mg/l, the majority of the organic material could be oxidized through sulfate reduction with a corresponding decrease in methane formation.

In the experiments reported here, 55 to 85 percent of the sulfate has been reduced. In addition to competing with methanogens and adversely affecting organic reduction, sulfate reducers reduce sulfates and reduced sulfur species interfere positively in the COD procedure. This results in higher final effluent COD values and the process appears to be producing relatively poor organics removal when it actually is providing rather good treatment with respect to "organic COD". In order to confirm the above arguments, laboratory scale experimentation was initiated. The main objective of the laboratory scale reactor was to determine the optimum sulphate to COD ratio that could be handled by anaerobic treatment. The results obtained so far are presented here.

MATERIALS AND METHODS

Reactors

Three separate pilot scale reactors and three laboratory scale reactors were fabricated and installed at the EPA's Testing and Evaluation (T&E) Facility in Cincinnati. Two pilot scale systems had a total reactor volume of 334 liters each and were operated using diatomaceous earth (DE) and granular activated carbon (GAC) respectively as their media. The third system containing sand consisted of two reactors connected in series, each having a reactor volume of approximately 66 liters. The three pilot scale systems are shown schematically in Figures 1 and 2; the physical characteristics of all three pilot systems are summarized in Table I.

The recirculation ratios necessary to maintain a 20 percent bed expansion at an empty bed contact time (EBCT) of six hours for the DE, GAC and sand systems were 12.7, 57.6 and 61.2., respectively.

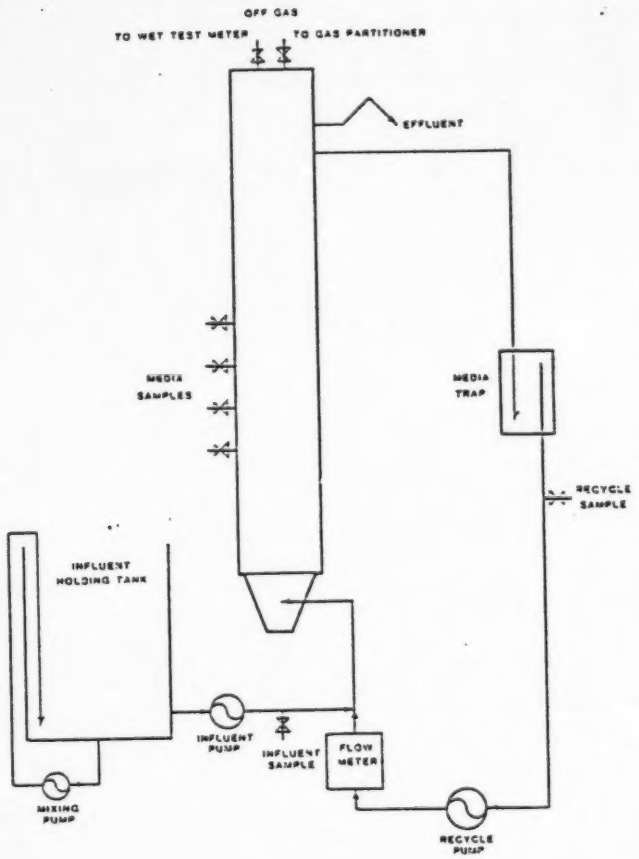

FIGURE 1. Schematic Diagram of the GAC and D.E. Media Processes

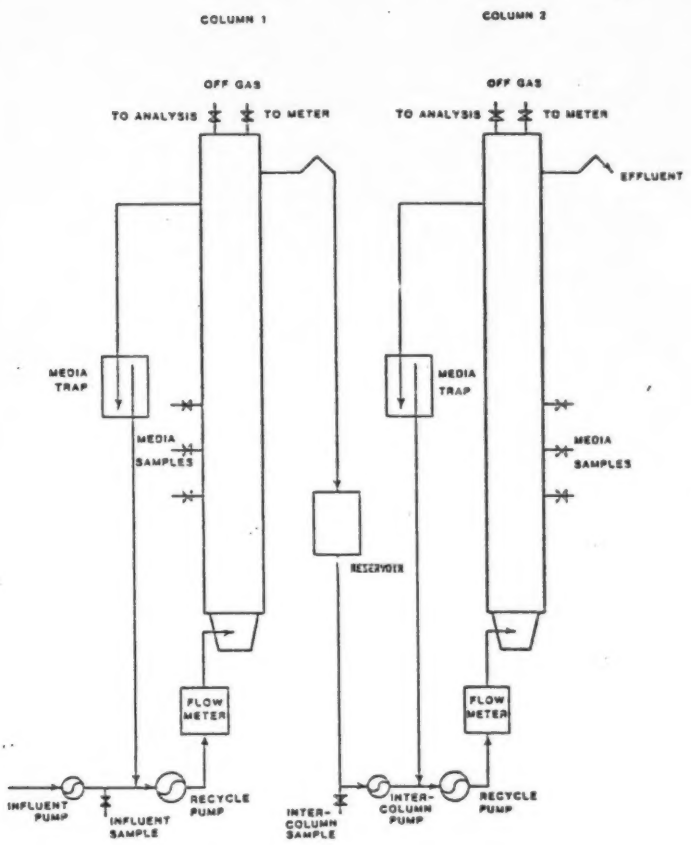

FIGURE 2. Schematic Diagram of the Sand Media Processes

The two laboratory scale reactors were constructed with a total volume of 3 liters each. The reactor model is schematically represented in Figure 3. Important physical characteristics of the columns are summarized in Table II.

Based on the parameters given below the minimum velocity of fluidization for the laboratory reactors was calculated to be approximately 4.2 ft/hr (0.52 gallons per minute per sq. ft).

TABLE I. SUMMARY OF THE PHYSICAL CHARACTERISTICS OF THE PILOT ANAEROBIC SYSTEMS

Media Type	Diatomaceous Earth	GAC	Sand
Media Size	0.34	0.71	0.37
No. of Reactors	1	1	2 (in series)
Reactor Diameter cm(in)	30.5 (12)	30.5 (12)	15.2 (6)
Reactor Height m(ft)	4.57 (15)	4.57 (15)	3.66 (12)
Static Bed Height m(ft)	1.52 (5.0)	1.52 (5)	1.94 (6.4)

TABLE II. SUMMARY OF PHYSICAL CHARACTERISTICS OF LABORATORY REACTORS

Height of the reactor	=	5 ft
Diameter of the reactor	=	2 in
Cross-sectional area	=	3.162 sq. inches
Volume of reactor	=	3.089 liters
Media used	=	Diatomaceous Earth
Dry density of media	=	25.5 lb/ft^3 (408.5 kg/cm^3)
Specific gravity of media	=	1.17
Volume of media used (Initial)	=	1.24 liters
Initial height of bed (unexpanded)	=	1.25 ft

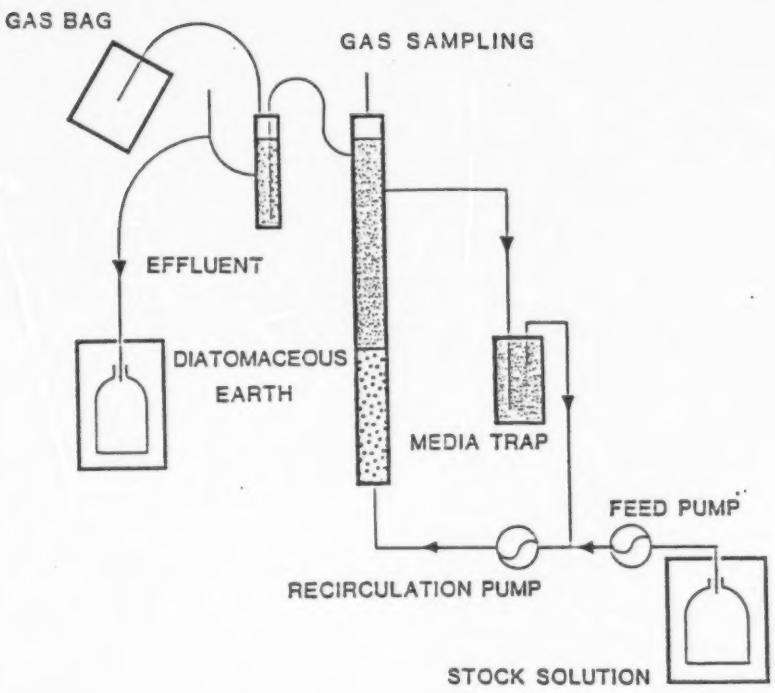

FIGURE 3. Schematic Diagram of the Laboratory Anaerobic Reactor

Pilot Plant Operation

The first process brought on line utilized the sand media system. The system was seeded with about 10 liters of sludge from the anaerobic digestors at the Mill Creek Wastewater Treatment Plant in July 1980 and was operated at a high hydraulic residence time (HRT) on primary effluent for several months before comprehensive sampling and analysis was initiated. A similar seeding and equilibration protocol was followed for the DE and GAC processes.

Tables III, IV, and V present summaries of the different experimental runs made on the anaerobic, expanded-bed processes. The major variable in the operation of DE and GAC systems has been the HRT at which the systems were operated. The sand system has been operated over a wide range of HRT's but has also utilized a number of different substrates as system feeds.

Lab Scale System Operation

Prior to the operation of the system, the reactors were filled with the media and operated using water to stabilize the expanded bed height and the flow pattern characteristics of the reactor. The expanded bed height stabilized at 18" (1.5 ft) and the excess media which flowed out of the reactors was trapped in the media trap. Once stablized the reactors were seeded with a mixture of primary and secondary sludge from the anaerobic digestors at the Oxford Municipal Treatment Plant. The influent for the reactors was synthetic wastewater having an average strength of 170 mg/l of total organic carbon (approximately 550 mg/l COD). The composition of the synthetic wastewater is in Table VI.

The operation of the reactors was started in September 1984, with a detention time of 12 hours. The reactors were operated at the same detention time until equilibrium was reached.

Sampling and Analysis

A comprehensive analytical program was established to evaluate the operation and performance of the anaerobic, expanded-bed processes. The basic program is summarized in the sampling and analysis matrix, shown as Table VII. The methods used were as given in, Standard Methods (14) or were automated versions of the Standard Methods procedures.

Methane determinations were occasionally performed on the process effluents, and the analyses were made using conventional gas-liquid chromatographic techniques with a flame ionization detector. Additionally, the total organic carbon measurements were made using an Astro Resources Model 1100 Analyser for the pilot scale studies and Dohrmann Model DC-80 for the lab scale.

TABLE III. SUMMARY OF RUNS CONDUCTED ON THE SAND SYSTEM

Run No.	Date	No. of Days	HRT (h)	Feed
seeded	7/9/80			
11	1/1 - 2/3/81	33	24	PE[a]
12	2/10 - 5/12	100	24	PE
13	5/13 - 5/27	14	20	PE
14	5/28 - 6/11	14	16	PE
15	6/12 - 7/23	41	12	PE + HA[b]
16	8/7 - 8/19	12	12	PE + HA
17	8/20 - 9/1	12	12	AS[e] + HA
18	9/2 - 9/10	8	12	AS[e] + HA + NaAc[c]
19	9/11 - 12/23	103	12	Slender[f]
110	12/24 - 1/14/82	27	6	Slender[f]
111	1/15 - 3/16	60	5	PE
112	3/17 - 4/21	34	9	PE
113	4/22 - 7/7	86	6	PE
114	7/8 - 9/3	27	5	MC - PE[d]
115	9/4 - 9/23	19	10	MC - PE
116	9/24 - 10/16	22	9	MC - PE
117	10/17 - 11/1	15	15	MC - PE
118	11/2 - 11/26	24	9	MC - PE
119	11/27 - 12/23	26	5	MC - PE
120	12/24 - 12/31	7	9	MC - PE
121	1/1/83 - 1/31	31	7	MC - PE

[a] primary effluent [b] acetic acid [c] sodium acetate
[d] Muddy Creek STP, primary effluent [e] Activated sludge effluent
[f] Carnation Instant Slender

TABLE IV. SUMMARY OF RUNS CONDUCTED ON THE D.E. SYSTEM

Run No.	Date	No. of Days	HRT (h)	Feed
seeded	8/9/81			
G1	3/1 - 4/14/82	45	24	PE[a]
G2	4/15 - 5/30	45	10	PE
G3	6/1 - 6/31	30	12	PE
G4	7/1 - 7/14	14	8	PE
G5	7/23 - 9/3	42	9	PE
G6	9/4 - 10/8	34	13	PE
G7	10/9 - 10/26	17	16	PE
G8	10/27 - 11/15	19	30	PE
G9	11/21 - 12/7	16	21	PE
G10	12/8 - 12/31	23	15	PE
G11	1/1/83 - 3/1	60	14	PE
G12	3/2 - 4/7	35	8	PE

[a]primary effluent

TABLE V. SUMMARY OF RUNS CONDUCTED ON THE G.A.C. SYSTEM

Run No.	Date	No. of Days	HRT (h)	Feed
seeded	8/11/81			
H1	3/1 - 4/21/82	50	24	PE[a]
H2	4/22 - 5/30	38	7	PE
H3	6/1 - 6/30	30	3	PE
H4	7/1 - 7/31	31	7	PE
H5	8/1 - 8/26	25	6	PE
H6	8/31 - 10/1	32	4	PE
H7	10/9 - 12/15	66	12	PE
H8	12/6 - 12/31	15	9	PE
H9	1/1/83 - 1/21	20	8	PE
H10	1/22 - 4/13	90	6	PE

[a] primary effluent

TABLE VI. SYNTHETIC WASTEWATER COMPOSITION

1.	Yeast Extract (Difco chemicals)	200 mg/l
2.	Bacto Peptone (Difco chemicals)	200 mg/l
3.	Soluble Starch (Fisher chemicals)	100 mg/l
4.	Urea	50 mg/l
5.	Sodium Bicarbonate	300 mg/l
6.	Ferric Chloride	0.02 mg/l
7.	Calcium Chloride	36 mg/l
8.	Magnesium Sulfate	22 mg/l
9.	Ammonium Chloride	2 mg/l
10.	Potassium Hydrogen Phosphate	8.5 mg/l
11.	Potassium Phosphate	22.5 mg/l
12.	Sodium Phosphate	33.0 mg/l
13.	Citric Acid	20.0 mg/l
14.	Cobalt Chloride	0.5 mg/l
15.	Nickel Chloride	0.5 mg/l

TABLE VII. SAMPLING ARRAYS

	pH	Temp	Alk.	Vol. Acids	Turb.	BOD_5	COD	COD_f	TOC	CH_4 & CO_2	NH_3-N	NO_3-N
PILOT SCALE												
Feed	3D	+	3D	2	+	7	2	2	+	+	2	2
Eff.	3D	+	3D	2	3D	7	2	2	+	+	2	2
Off Gas	+	+	+	+	+	+	+	+	+	7	+	+
LAB SCALE												
Feed	1	1	1	7	+	+	1	+	1	+	+	+
Eff.	1	1	1	7	+	+	1	+	1	+	+	+
Off Gas	+	+	+	+	+	+	+	+	+	7	+	+

	TKN	Total P	Sulfides	Sulfites	Sulfates	TSS	VSS
PILOT SCALE							
Feed	2	2	1	1	1	2	2
Eff.	2	2	1	1	1	2	2
Off Gas	+	+	+	+	+	+	+
LAB SCALE							
Feed	+	+	+	+	2	2	2
Eff.	+	+	+	+	2	2	2
Off Gas	+	+	+	+	+	+	+

LEGEND: 3D = Thrice daily 2 = every other day 1 = Once daily 7 = once a week

RESULTS

Pilot Scale Studies

A) Sand Media Process

Over a 25 month period, 21 runs were conducted on the system with the sand media. The first 13 runs were conducted on primary effluent from the Mill Creek Wastewater Treatment Plant, the location of the T&E Facility, or on artificial substrates, as indicated in Table III. The wastewater entering the Mill Creek plant has a rather high industrial component, which results in an unusually high strength wastewater. Therefore, to gather additional perspective on the process, the feed for runs 14 through 21 was changed to primary effluent from the Muddy Creek Wastewater Treatment Plant. The Muddy Creek wastewater is essentially domestic in origin, and primary effluent from the Muddy Creek plant was transported to the T&E Facility two or three times per week during that six month portion of the study.

Table VIII presents the average COD and TSS concentrations observed for each run, and the corresponding percent removals. Considerable variability is apparent in the data, especially the COD removals. However, since HRT's were being varied considerably, the variability is not surprising. The data in Table VIII were condensed, and a summary is presented as Table IX.

During runs 1 through 13 the mean effluent COD concentration was 143 mg/l, which corresponds to an average COD removal of 43 percent. The average TSS removal of 67 percent produced a mean effluent TSS concentration of 39 mg/l.

Runs 14 through 21 used the significantly weaker Muddy Creek primary effluent. Mean influent COD concentrations averaged 78 mg/l, compared to 263 mg/l for the previous 13 runs. Average COD removals were 23 percent, with a mean effluent COD of 60 mg/l. The average effluent TSS concentration during this portion of the study was 13 mg/l, with a standard deviation of 12 mg/l.

Tables X and XI present the ammonia-N, TKN, and total-P and the pH, alkalinity, and turbidity data for each run, respectively. The increases observed in NH3-N concentrations are typical of anaerobic systems, and the relatively low phosphorus removals are characteristic of biological systems with low growth rates.

Thc effluent from the process usually appeared hazy, and the turbidity data in Table XI, and the previously discussed effluent TSS data, indicate that the effluent contained an appreciable amount of colloidal, or near-colloidal, material.

TABLE VIII. AVERAGE COD AND TSS CONCENTRATIONS FOR EACH RUN WITH THE SAND MEDIA

Run No.	COD			TSS		
	Inf. (mg/l)	Eff. (mg/l)	Removal (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)
11	455	189	58	214	45	79
12	330	140	58	153	26	83
13	116	93	20	140	35	75
14	104	83	20	141	38	73
15	224	157	30	176	74	58
16	221	128	42	104	29	72
17	163	91	44	73	22	70
18	322	141	56	74	17	77
19	354	168	53	84	32	62
110	192	73	62	75	30	60
111	326	142	56	213	49	77
112	282	213	25	92	69	25
113	336	235	30	118	47	60
114	68	53	22	35	18	49
115	85	61	28	29	5	83
116	101	69	32	22	9	59
117	99	97	2	27	38	
118	78	59	24	19	6	68
119	67	53	21	22	14	36
120	47	38	19	7	1	86
121	77	51	34	20	10	50

TABLE IX. SUMMARY OF COD AND TSS DATA[a], WITH STANDARD DEVIATIONS, FOR THE SYSTEM WITH SAND MEDIA

Runs	COD			TSS		
	Inf. (mg/l)	Eff. (mg/l)	Removal (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)
Hill Creek; Runs 1-13	263 (103)[b]	143 (50)	43 (16)	127 (50)	39 (17)	67 (15)
Muddy Creek; Runs 14-21	78 (18)	60 (17)	23 (10)	23 (8)	13 (12)	54 (28)
All Runs	193 (123)	111 (57)	35 (17)	88 (65)	29 (20)	62 (21)

[a]Values are summaries of run means presented in Table VIII.
[b]Standard deviations in ( ).

TABLE X. MEAN AMMONIA-N, TKN, AND TOTAL-P CONCENTRATIONS FOR THE SAND MEDIA PROCESS

Run No.	NH_3-N			TKN			Total-P		
	Inf. (mg/l)	Eff. (mg/l)	Increase (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)
111	20.1	24.5	22	26.5	25.6	3.4	4.8	3.9	18.8
112	14.4	17.9	24	20.0	20.0	0	4.0	3.9	2.5
113	23.0	27.0	17	31.6	30.7	2.8	5.9	5.1	13.6
114	14.6	17.2	18	16.4	18.9	-	5.1	4.6	9.8
115	10.6	19.0	79	16.0	21.8	-	6.1	5.0	18.0
116	7.7	12.4	74	10.3	15.4	-	4.5	3.6	20.0
117	16.9	23.2	37	15.9	22.1	-	7.1	5.7	19.7
118	7.4	6.3	-	9.4	11.0	-	6.0	5.2	13.3
119	4.0	3.2	-	5.8	5.2	10.3	3.6	3.5	2.8
120	2.3	4.0	74	5.1	4.0	21.6	2.2	1.5	31.8
121	10.6	11.3	7	11.4	11.4	5.8	3.7	3.1	16.2

TABLE XI. MEAN pH, ALKALINITY, AND TURBIDITY VALUES FOR THE SAND MEDIA PROCESS

Run No.	pH[a]		Alkalinity[b]		Turbidity
	Inf.	Eff.	Inf. (mg/l)	Eff. (mg/l)	Eff. (NTU)
111	7.6	7.3	254	464	-
112	7.3	7.5	243	438	108
113	7.3	7.4	252	490	154
114	7.5	7.3	211	248	47
115	-	-	-	-	-
116	7.4	7.1	190	215	30
117	7.5	7.2	227	253	37
118	7.4	7.2	216	224	16
119	7.4	7.1	227	224	12
120	7.4	7.0	199	196	3
121	7.6	7.2	215	221	19

[a]Std. units
[b]as CaCO3

B) Diatomaceous Earth Process

A total of 12 runs were conducted with the D.E. media system during a 13 month period. The feed was always primary effluent from the Mill Creek plant, and the only operating variable was the HRT, which ranged from 8 to 30 hours.

Table XII presents the average COD and TSS results for each run. The mean influent COD concentration, for all runs, was 262 mg/l, with a standard deviation of 108. The average COD removal was only 26 percent, with a standard deviation of 20 percent, which is considerably lower than the 43 percent mean COD removal observed for the sand media process treating Mill Creek primary effluents.

The average effluent TSS concentration, for all runs, was 55 mg/l (standard deviation = 25) compared to 29 mg/l for the sand system (standard deviation = 20). TSS removals for all runs averaged 45 percent, with a standard deviation of 19 percent.

Table XIII presents the average concentrations for NH3-N, TKN, and total-P for the D.E media process. Trends similar to those observed for the sand media process were observed.

The alkalinity, pH, and turbidity data are summarized in Table XIV. The mean turbidity for all runs was 106 NTU, which clearly reflects the turbid characteristics of the effluent.

C) GAC Media Process

A total of 10 runs were conducted with the GAC media process over a 14 month period. The feed to the process was always Mill Creek primary effluent, and the only process variable changed during the study was the HRT.

Table XV presents the average COD and TSS data for each run. The mean influent COD concentration was 236 mg/l for all runs, and the average COD removal was 39 percent. TSS removal averaged 58 percent for all runs, with a standard deviation of 14 percent, which produced a mean effluent TSS concentration of 57 mg/l.

The ammonia-N, TKN, and total-P data for the GAC media process are reported in Table XVI, and the pH, alkalinity, and turbidity data are presented in Table XVII. These data exhibit trends similar to the data for the sand and DE media processes, previously discussed.

TABLE XII. AVERAGE COD AND TSS CONCENTRATIONS FOR EACH RUN WITH THE D.E. MEDIA

Run No.	COD			TSS		
	Inf. (mg/l)	Eff. (mg/l)	Removal (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)
G1	234	135	42	85	54	36
G2	345	261	24	98	75	23
G3	293	241	18	130	42	68
G4	313	249	20	146	127	13
G5	156	136	13	97	47	52
G6	328	269	18	79	44	44
G7	465	291	37	132	54	59
G8	389	98	75	90	49	46
G9	103	112	-	78	36	54
G10	105	102	3	73	18	75
G11	204	172	16	92	49	47
G12	213	179	16	76	59	22
Mean	262	187	26	98	55	45
Standard Deviation	108	68	20	23	25	19

TABLE XIII. MEAN AMMONIA-N, TKN, AND TOTAL-P CONCENTRATIONS FOR THE D.E. MEDIA PROCESS

	NH_3-N			TKN			Total-P		
Run No.	Inf. (mg/l)	Eff. (mg/l)	Increase (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)
G1	15.0	20.0	33	21.3	21.2	.5	4.22	3.72	11.8
G2	23.9	28.5	19	32.8	32.3	1.5	5.89	5.48	7.0
G3	22.2	24.9	27	30.0	30.1	-	5.47	4.98	9.0
G4	22.0	24.0	9	29.1	28.9	.7	6.87	5.89	14.3
G5	25.9	26.1	1	34.1	32.5	4.7	4.98	4.36	12.4
G6	30.1	30.4	1	37.0	35.9	3.0	4.54	3.94	13.2
G7	35.4	37.8	7	43.1	42.7	.9	4.87	4.85	.4
G8	30.5	34.5	13	38.2	37.5	1.8	5.55	4.47	19.5
G9	20.6	23.1	13	26.0	32.4	-	3.66	4.65	-
G10	22.6	25.9	15	27.3	24.8	9.2	3.68	2.75	25.3
G11	31.3	33.9	8	43.9	41.8	4.8	4.28	3.16	26.2
G12	30.8	33.4	8	43.9	43.5	.9	4.58	4.20	8.3

TABLE XIV. MEAN pH, ALKALINITY, AND TURBIDITY VALUES *FOR THE D.E. MEDIA PROCESS*

Run No.	pH[a]		Alkalinity[b]		Turbidity
	Inf.	Eff.	Inf. (mg/l)	Eff. (mg/l)	Eff. (NTU)
G1	7.4	7.5	240	462	115
G2	7.2	7.5	276	558	217
G3	7.2	7.5	285	478	175
G4	7.2	7.6	277	458	162
G5	7.2	7.5	296	490	70
G6	7.1	7.3	355	570	86
G7	7.2	7.4	356	576	62
G8	7.2	7.7	367	615	57
G9	7.3	7.9	307	450	108
G10	7.2	7.7	279	456	83
G11	7.3	7.6	321	552	55
G12	7.2	7.3	276	559	76

[a]Std. Units
[b]as $CaCO_3$

TABLE XV. AVERAGE COD AND TSS CONCENTRATIONS FOR EACH RUN WITH THE GAC MEDIA

Run No.	COD			TSS		
	Inf. (mg/l)	Eff. (mg/l)	Removal (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)
H1	246	92	63	99	19	81
H2	411	200	51	189	86	55
H3	312	232	26	154	102	34
H4	188	103	45	150	50	67
H5	163	67	59	127	46	64
H6	390	244	37	151	87	42
H7	190	126	34	113	47	58
H8	75	63	16	117	34	71
H9	204	129	37	129	51	61
H10	179	136	24	99	50	50
Mean	236	139	39	133	57	58
Standard Deviation	100	61	14	27	18	14

TABLE XVI. MEAN AMMONIA-N, TKN, AND TOTAL-P CONCENTRATIONS FOR THE G.A.C. MEDIA PROCESS

	NH_3-N			TKN			Total-P		
Run No.	Inf. (mg/l)	Eff. (mg/l)	Increase (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)	Inf. (mg/l)	Eff. (mg/l)	Removal (%)
H1	18.3	20.4	11	21.9	18.9	13.7	4.40	3.66	16.8
H2	25.2	28.9	15	36.0	31.9	11.4	7.36	6.01	18.3
H3	22.7	25.5	12	30.8	28.9	6.2	6.33	5.42	14.4
H4	27.5	31.1	14	37.8	33.9	10.3	6.44	5.17	19.7
H5	25.8	28.9	12	36.8	32.2	12.5	5.87	4.91	16.4
H6	30.7	30.6	-	38.6	34.9	9.6	5.69	5.04	11.4
H7	31.6	24.9	10	36.9	36.8	.3	5.58	4.79	14.2
H8	25.4	27.8	9	28.5	24.6	13.7	4.19	2.91	30.5
H9	30.0	33.4	11	39.3	36.1	8.1	6.00	4.14	31.0
H10	29.9	33.3	11	42.5	40.2	5.4	4.76	3.95	17.0

TABLE XVII. MEAN pH, ALKALINITY, AND TURBIDITY VALUES FOR THE G.A.C. MEDIA PROCESS

Run No.	pH[a]		Alkalinity[b]		Turbidity
	Inf.	Eff.	Inf. (mg/l)	Eff. (mg/l)	Eff. (NTU)
H1	7.3	7.7	240	480	77
H2	7.3	7.8	280	512	168
H3	7.3	7.4	298	434	194
H4	7.6	7.8	329	517	67
H5	7.6	7.8	350	497	43
H6	-	-	-	-	
H7	7.7	7.9	420	541	87
H8	7.5	7.9	340	466	110
H9	7.6	7.8	361	501	89
H10	7.7	7.8	349	539	70

[a]Std. units
[b]as CaCO3

Laboratory Scale Study

During the conduct of the laboratory scale study the two reactors (A and B) were run for three different hydraulic detention times of 12 hours, 15 hours and 24 hours. The reactors were first set-up in operation and were kept on a 12 hour detention time until they came to equilibrium. The summary of the two process control parameters viz. pH and alkalinity for the three detention times are shown in Table XVIII. The summarized total organic carbon along with the statistical control limits for the different detention times are presented in Table XIX. Table XX shows the average percent removals of TOC and COD for effluent A and B for the different detention times.

Six different levels of concentrations of sulfate (introduced as sodium sulfate) have been introduced in the influent. The effects of different concentrations of sulfate on the removal efficiency are shown in Table XXI. Influent and effluent concentrations of sulfate and percent removals of sulfate are shown in Table XXII.

Table XVIII. SUMMARY OF pH AND ALKALINITY VALUES

	pH			Alkalinity		
	Inf.	Eff. A	Eff. B	Inf.	Eff. A	Eff. B
Mean	7.08	7.36	7.47	359	527	516
Standard Deviation	0.23	0.30	0.33	28	33	29
Upper Control Limit	7.54	7.96	8.07	415	592	575
Lower Control Limit	6.62	6.66	6.86	304	461	458
Highest Value	7.48	7.94	8.05	408	576	594
Lowest Value	6.51	7.06	6.83	291	466	480

TABLE XIX. SUMMARY OF TOC (mg/1)

		MEAN	STAND. DEV.	UPPER CONTROL LIMIT	LOWER CONTROL LIMIT
	Inf.	177	6	190	165
t_d=12 hrs	Eff. A	62	12	86	38
	Eff. B	66	13	92	40
	Inf.	179	6	190	170
t_d=15 hrs	Eff. A	45	17	78	13
	Eff. B	58	16	89	27
	Inf.	166	10	186	147
t_d=24 hrs	Eff. A	46	11	67	25
	Eff. B	36	7	50	22

TABLE XX. TOC AND COD REMOVALS

Det. Times (hrs.)	Influent TOC (mg/1)	TOC Removal (%)	Influent COD (mg/1)	COD Removal (%)
12	177	64	554	65
15	179	71	528	71
24	166	75	491	77

COD:TOC ratio = 2.95 (average)

TABLE XXI. EFFECT OF SULFATE CONC. ON TOC and COD REMOVALS

Sulfate Conc. (mg/l)	TOC Removal %	COD Removal %
10	74	72
20	68	70
30	61	64
50	63	64
75	69	67
100	72	76

TABLE XXII. SULFATE CONCENTRATIONS

Influent Sulfate Conc. (mg/l)	Effluent Sulfate Conc. (mg/l)	Bulk Removal of Sulfate (mg/l)	% Removal of Sulfate
12	2	10	80
18	8	10	56
33	12	21	62
50	27	23	46
92	55	37	40

DISCUSSION

Figure 4 is a plot of reactor loading, gm COD applied/l·d, versus effluent COD, mg/l. As one would expect, the GAC system provided the best overall COD removal due to adsorption, the regression equation for the sand process has a slope about 76 percent greater than the DE process. It is interesting to note that over the range of loadings studied, the observed effluent COD concentrations were relatively linear functions of the mass loading.

The expanded-bed reactors used during this study can be modeled as plugflow reactors with recycle, but with the high recirculation ratios required, they can be simulated very accurately as continuous flow stirred tank reactors. The sand system can then be considered as two continuous flow stirred tank reactors in series and the DE system as a single continuous flow stirred tank reactor. Theoretically, the performance of the sand system should only be about four or five percent better than DE system, assuming first order kinetics.

The effective sizes of the DE and sand media are substantially different; therefore, the sand media has a specific area (m^2 per cm^3) 37 percent greater than the DE media. The difference in performance would seem to be related to surface area.

Conventional analysis of data to determine the first-order COD removal coefficient consists of plotting S_o-S_e/X_v versus S_e (15), where S_o and S_e are the influent and effluent COD concentrations, mg/l, X_v is the reactor volatile suspended solids, mg/l. Reactor VSS concentrations were not available for several of the earlier runs on the sand media process, and VSS sampling was minimized during the study to keep media losses as low as possible. For these reasons the data analysis consisted of plotting S_o-S_e/θ versus S_e, where θ is the theoretical residence time, hour.

Figures 5, 6, and 7 are the first-order plots (without the X_v term) for the sand, DE, and GAC media processes. The data for the systems are reasonably well behaved, having correlation coefficients of 0.81 to 0.85.

The difference in the surface areas would also relate to the active biomass accumulation in the reactors. The treatment efficiency of the processes is directly associated with the available active biomass to degrade the influent organics.

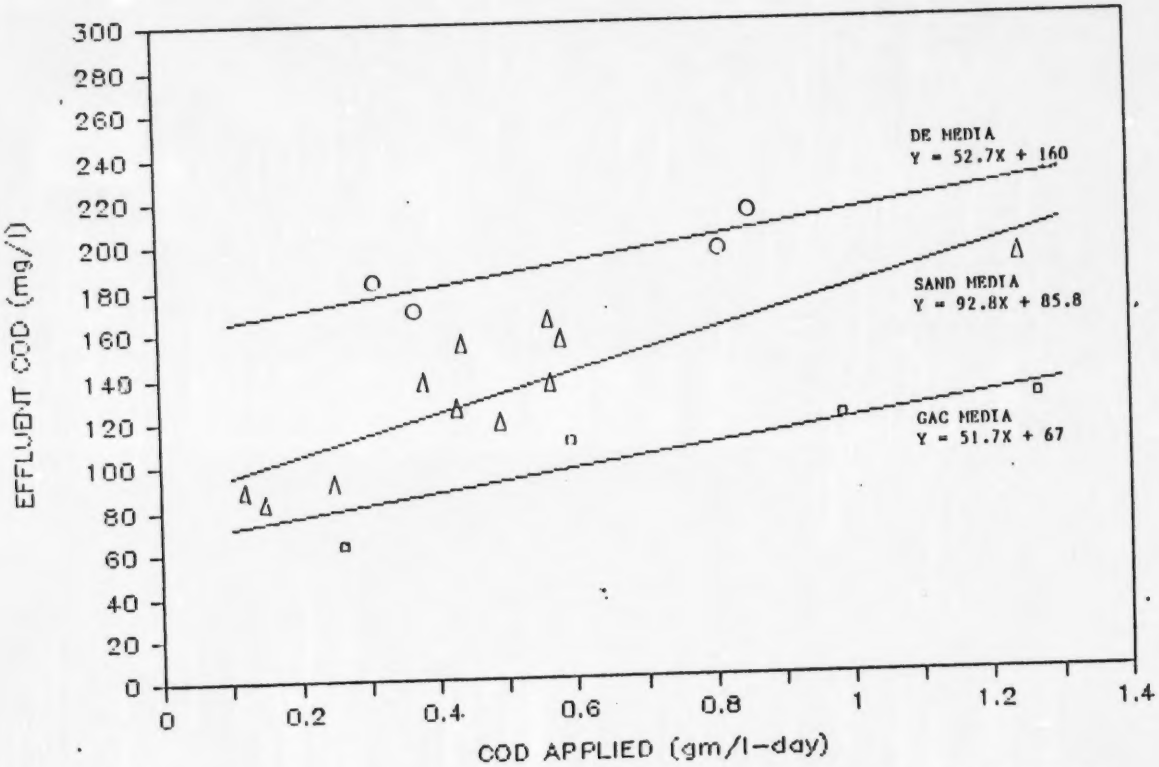

FIGURE 4. Effluent COD Versus COD applied for the Sand, Diatomaceous Earth and GAC Systems

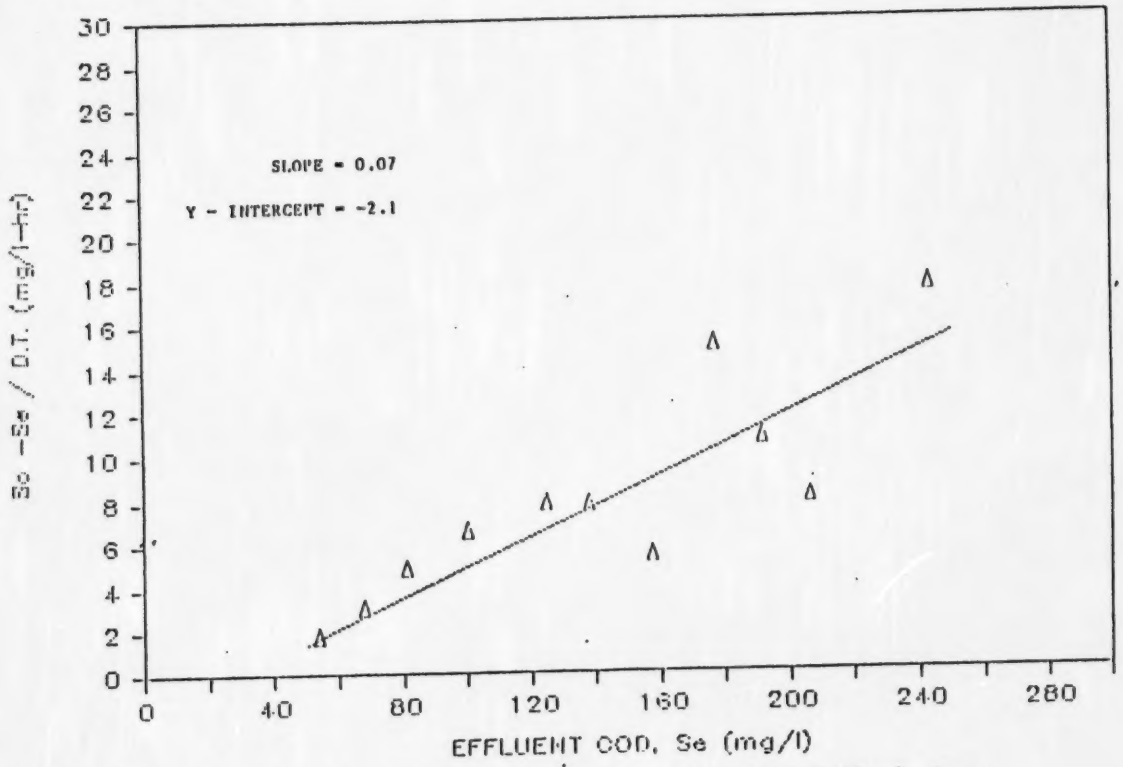

FIGURE 5. First Order Plot for the Sand Media System

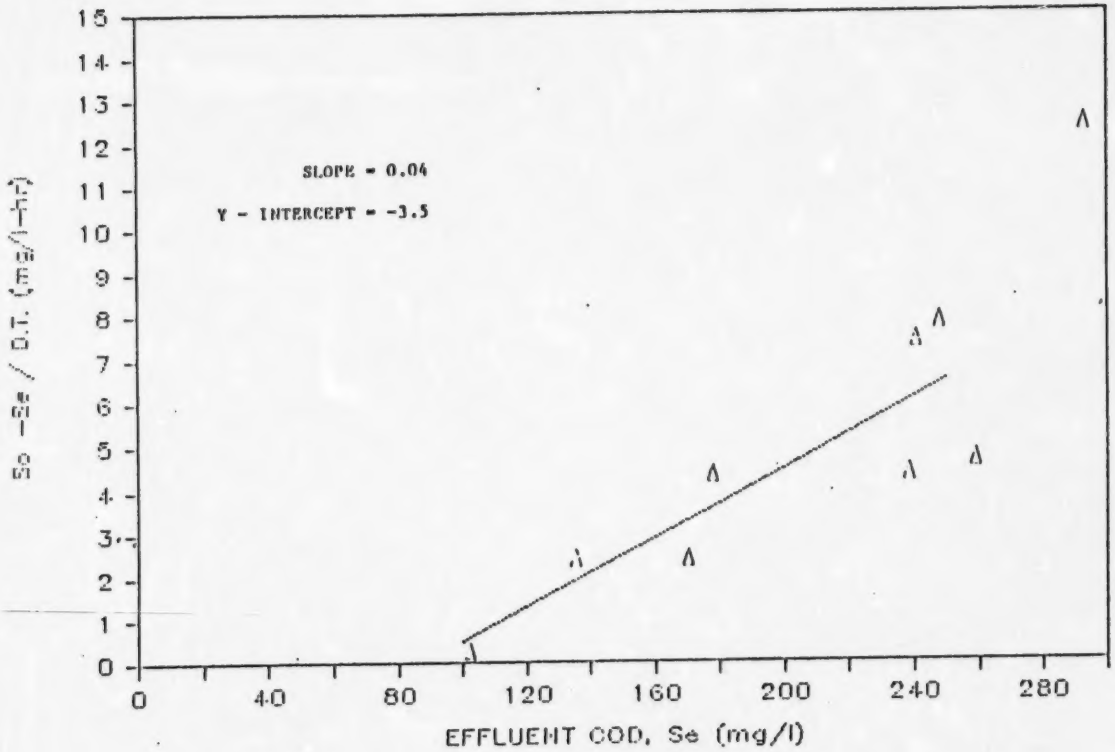

FIGURE 6. First Order Plot for the D.E. Media System

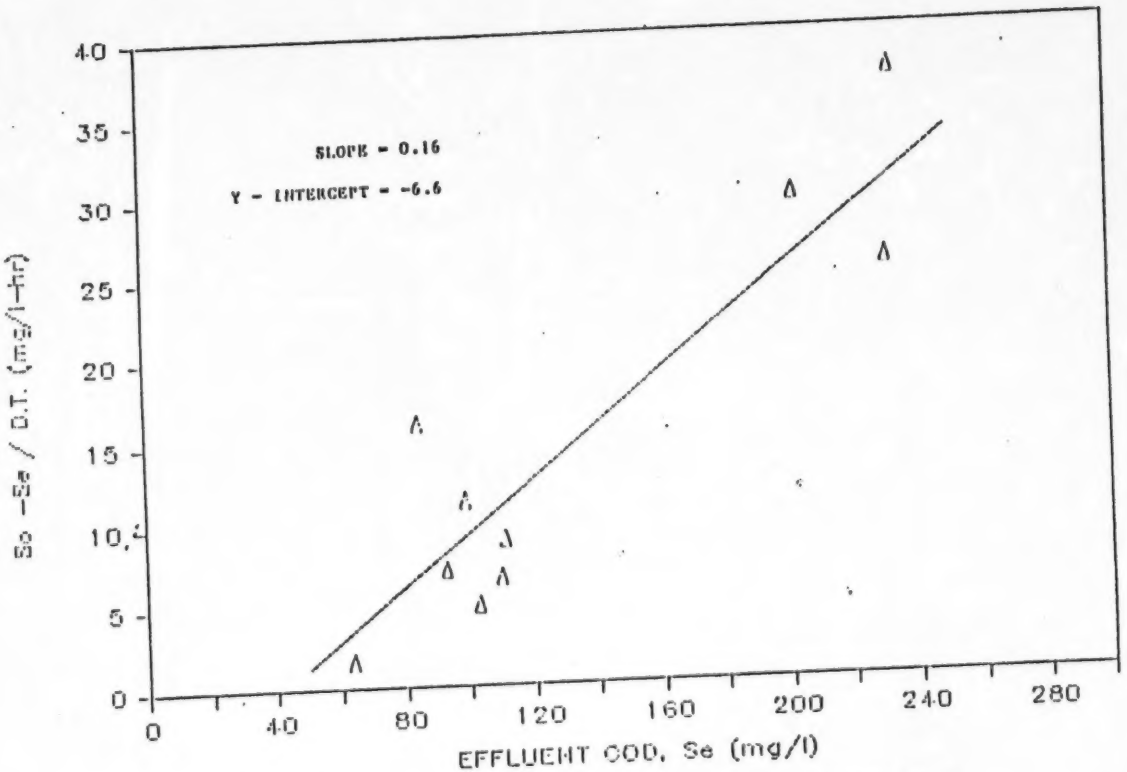

FIGURE 7. First Order Plot for the GAC Media System

Figures 8, 9 and 10 are plots of COD removal vs COD applied for all the three processes. Comparison of these plots indicates that the GAC process has the best performance, followed by the sand process and then the DE process. The difference in the performance between the sand and DE process can be attributed to difference in the surface area and to the available active biomass.

Sulfate, sulfite and sulfide were monitored for 89 days. During this period the mean influent sulfate concentrations to three pilot scale processes were 141, 168 and 216 mg/l as SO_4. Individual concentrations above 300 mg/l were observed on numerous occasions. Effluent sulfate concentrations were 66, 36 and 54 mg/l as SO_4, resulting in 53, 79 and 75% sulfate reduction. However, according to limited data available the sulfate reduction did not lead to a corresponding increase in either sulfites or sulfides, which indicated that elemental sulfur should be present in the system. In the pilot plant work conducted by Coulter, et al, (16) a white scum was observed near the effluent ports of the reactor and was reported to have a sulfur content of 18 percent by weight. A similar material was observed during this investigation, and semiquantitative analysis indicates a sulfur content of about 50 percent by dry weight. Additionally, hydrogen sulfide odor was not detected in the treated effluent. It can be postulated that sulfate reduction was occurring with sulfur being the end product.

This unusual reaction occurred simply because of a lack of organic matter to force the reduction reaction to sulfides. Energy transformation in microbial systems is essentially an electron transfer. The organic matter supplies the electrons which are transferred to sulfate as the ultimate acceptor. Initial transfer of electrons results in reduction of sulfates to sulfites and then to elemental sulfur. With sufficient electrons, the reduction reaction proceeds to sulfides. The failure of the reactions to proceed beyond elemental sulfur indicates a lack of readily available electrons. While this reaction is not unique, it is uncommon in wastewater systems and has not been reported in the wastewater literature. The presence of sulfide, elemental sulfur and sulfites also interfere with the COD analysis by exerting additional chemical oxygen demand. Thus the results from the COD analysis also include the inorganic oxygen demand due to the presence of these sulfur species. During the 89 day period the mean influent COD concentration measured for the sand, DE and GAC processes were 64, 174 and 153 mg/l and the mean effluent COD concentrations were 41, 151 and

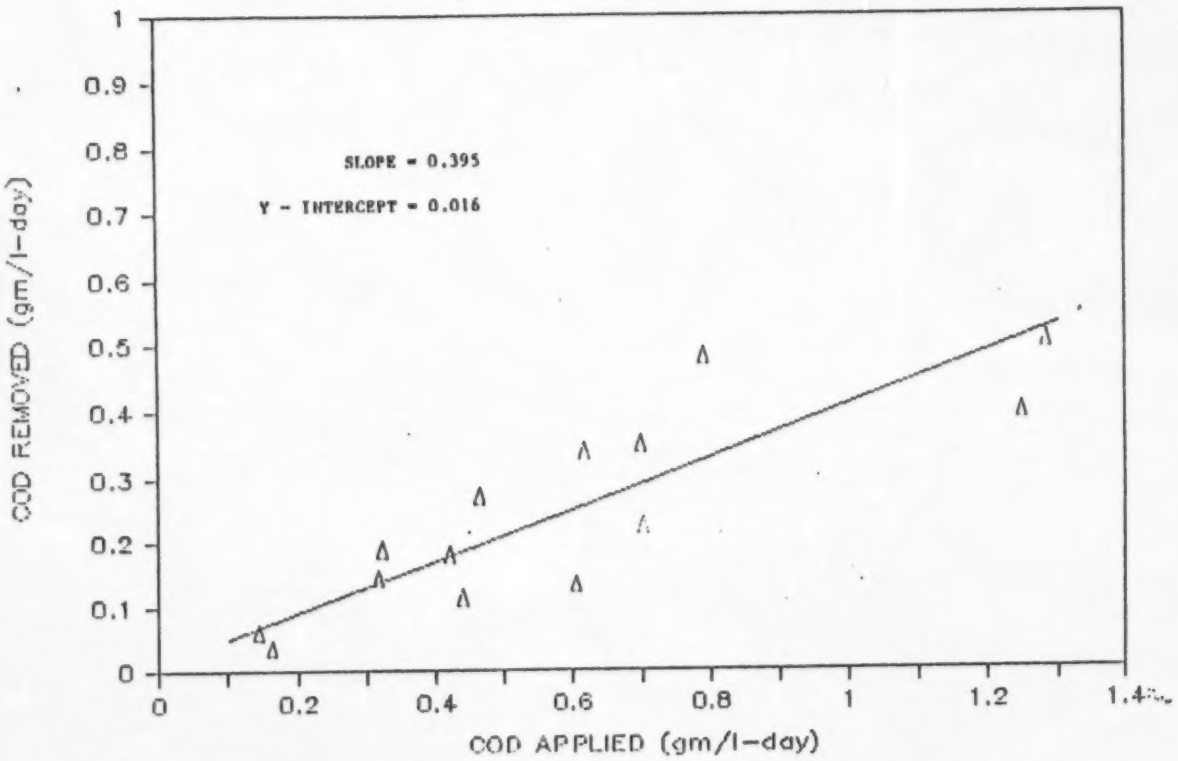

FIGURE 8. Bulk COD Removal Versus COD Loading for the Sand Media System

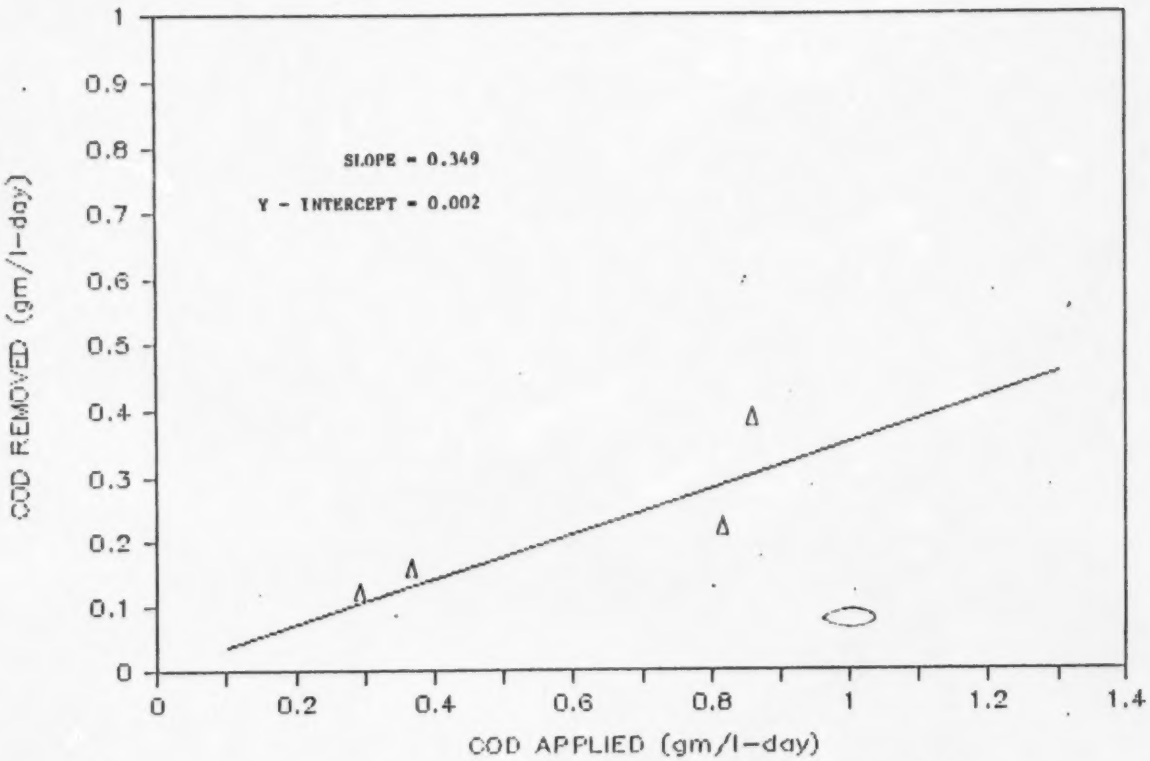

FIGURE 9. Bulk COD Removal Versus COD Loading for the D.E. Media System

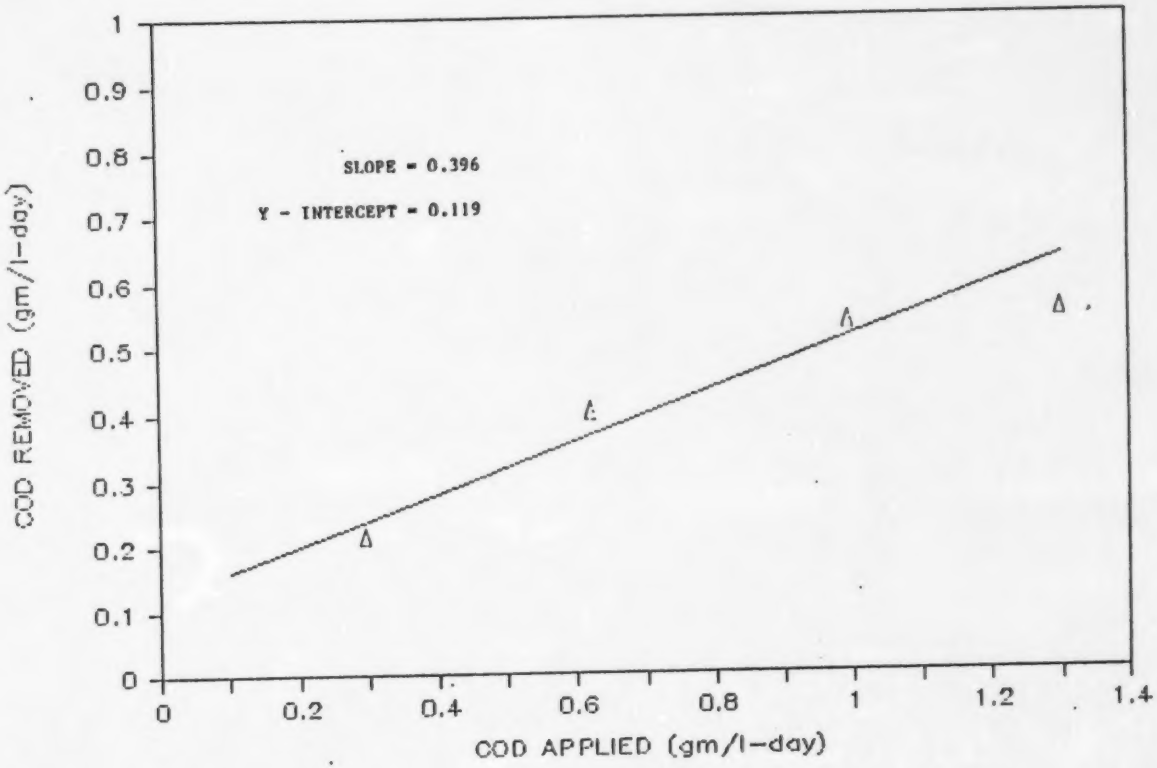

FIGURE 10. Bulk COD Removal Versus COD Loading for the GAC Media System

109 mg/l respectively. Table XXIII presents the measured COD's for this period and postulate COD's (based on theoretical calculations) due to organics only. The ongoing laboratory scale experiments were initiated to test the above postulate.

TABLE XXIII. COMPARISION BETWEEN APPARENT EFFLUENT COD AND COD REMOVAL CORRECTED FOR ELEMENTAL SULPHUR, SULPHIDE AND SULPHITE

Process	Influent COD mg/l	Effluent COD mg/l	COD Removal %	"Sulphur" COD (mg/l)	Corrected Effluent COD mg/l	Corrected COD Removal %
Sand	64	47	27	41	6	91
D.E.	174	151	13	114	37	79
GAC	153	109	29	72	37	77

Laboratory Scale Reactors

For the laboratory scale reactors, Figure 11 is a continuous plot of the total organic carbon (mg/l) represented as seven day moving averages, depicting the performance trend of the reactors. Evidently there is considerable effect on the removal efficiency due to change in operating conditions. However, the upset is only for a short duration as the reactors are self-equilibrating. Figure 12 is a plot of the removal efficiency versus the detention time. As evident, it shows a positive slope (0.91) indicating better removal efficiency at higher detention times. The coefficient of correlation (r) is 0.97. The detention times ranged from 12 hours to 24 hours and the removal efficiencies of both COD and TOC ranged between 65 to 75 percent. The average ratio COD/TOC was calculated to be 2.95.

Benedek (17) indicated that change in operating conditions instigated desorption of organics and change in substrate transfer to the bacterial film which explains the high effluent TOC immediately following a change in the detention time (or change in loading rate). The bacterial acclimation phases are also evident.

Initially an increase in sulfate concentration in the influent adversely affected the organic removal efficiencies (Figure 13). The amount of sulfate depletion varied but the fluctuation in the effluent sulfate concentration more or less followed the same trend as the influent sulfate concentration as shown in Figure 14. Increasing sulfate removal with increasing influent sulfate indicates the growth of sulfate reducing bacteria. However, decreasing percent removals imply that the growth is somewhat restricted. The cause of this limited growth is being investigated. Production of H_2S has been ascertained in the reactors. However due to the lack of sulfide measurements in the liquid phase no mass balance calculations have been made. With the data currently being collected on the ongoing experiments a mass balance on sulfur will be obtained. At the concentrations studied, the sulfate reduction did not affect the TOC and COD reductions significantly, probably due to process acclimatization.

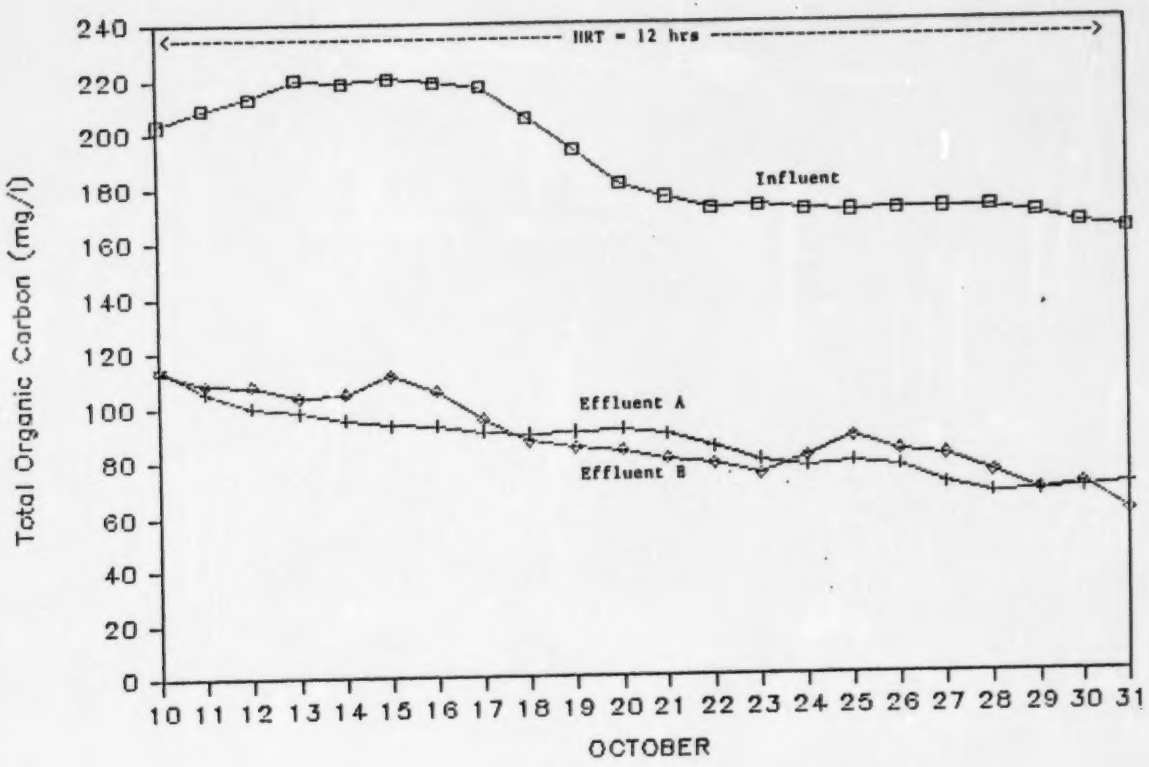

FIGURE 11a. Total Organic Carbon (7 day moving averages) in Laboratory Reactors

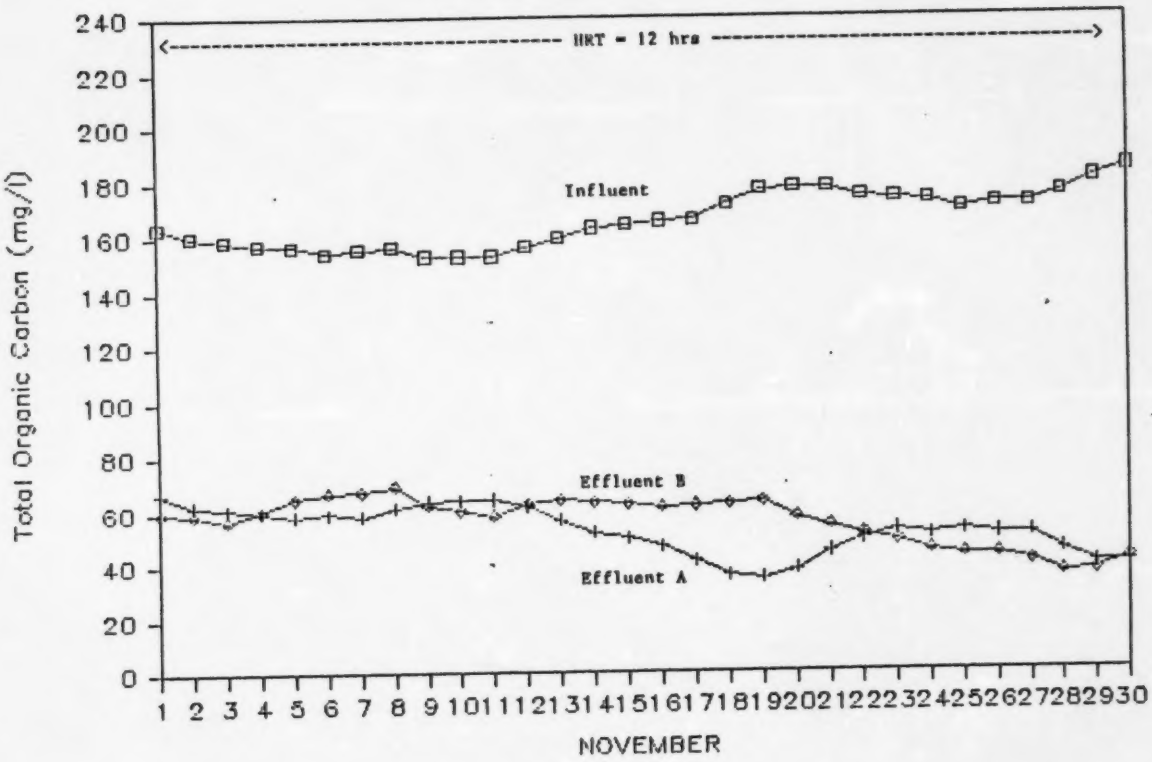

FIGURE 11b. Total Organic Carbon (7 day moving averages) in Laboratory Reactors

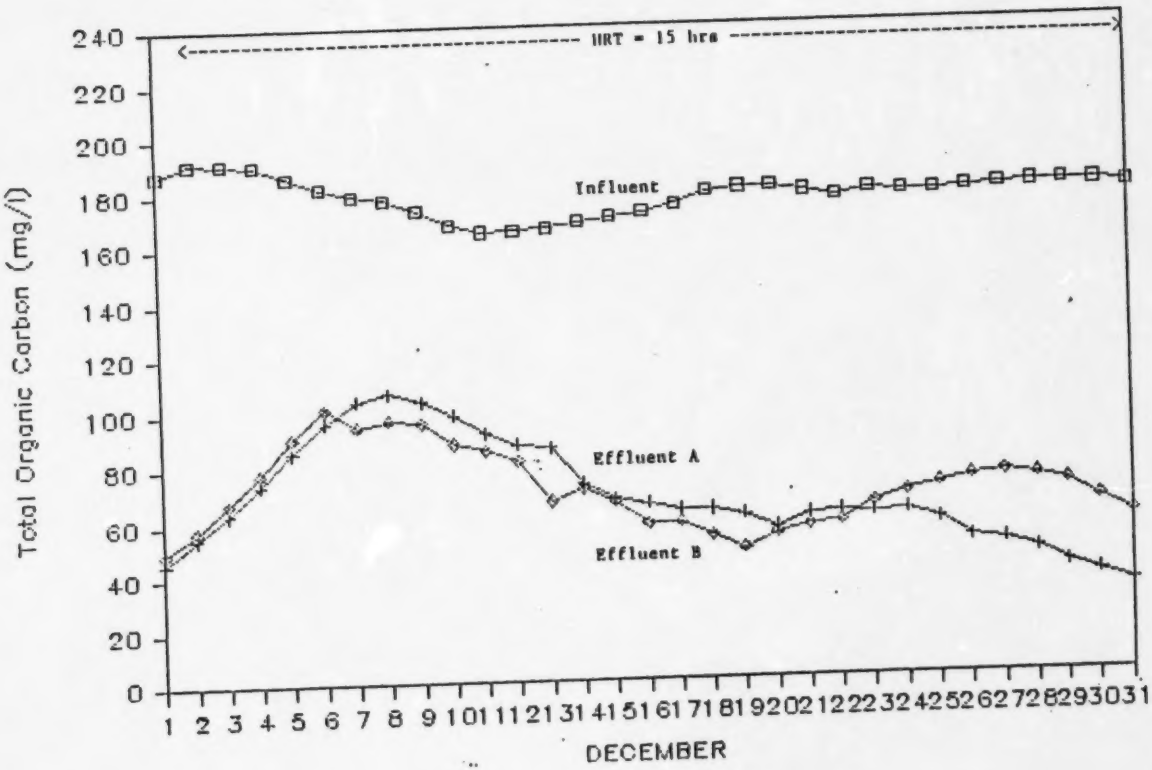

FIGURE 11c. Total Organic Carbon (7 day moving averages) in Laboratory Reactors

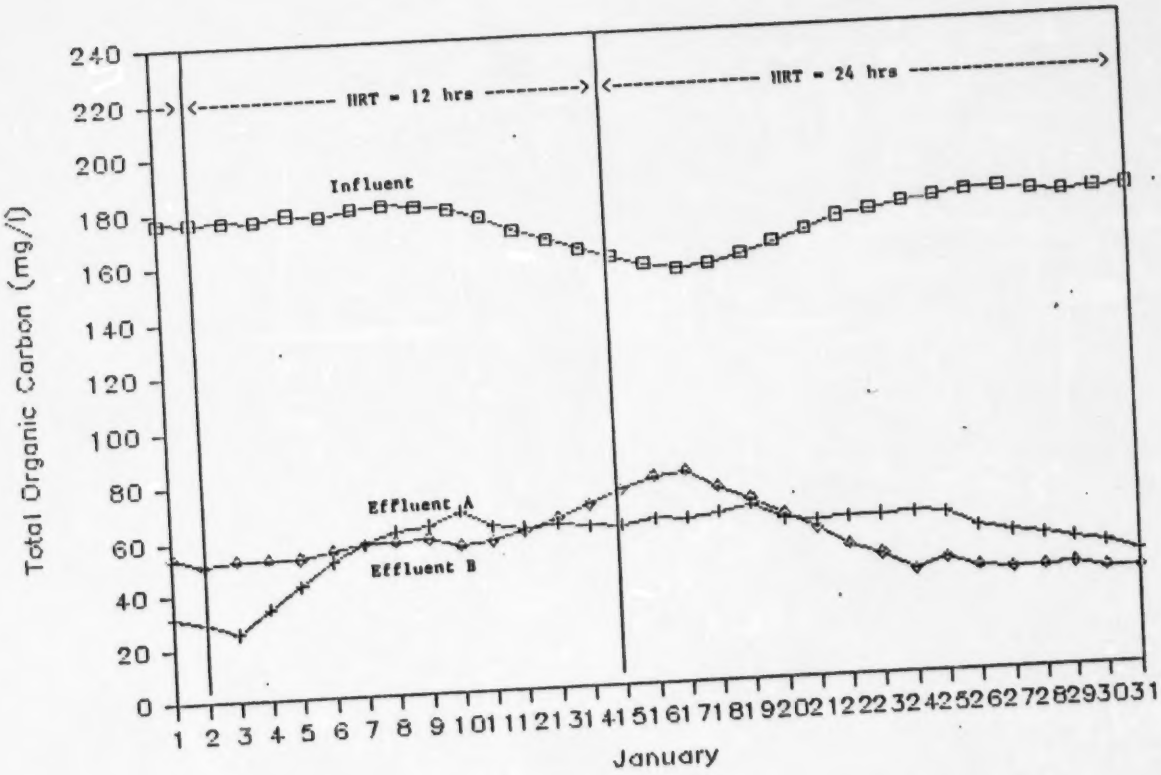

FIGURE 11d. Total Organic Carbon (7 day moving averages) in Laboratory Reactors

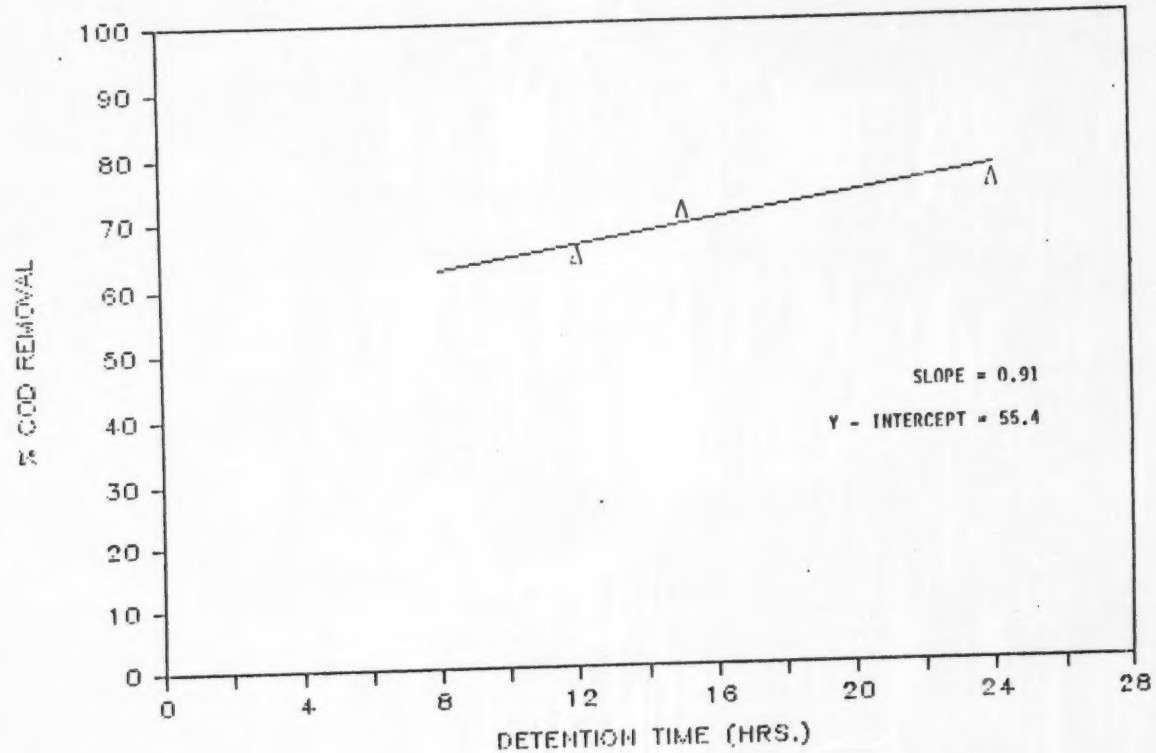

FIGURE 12. % COD Removal Versus Detention Time for the Laboratory Scale Reactors

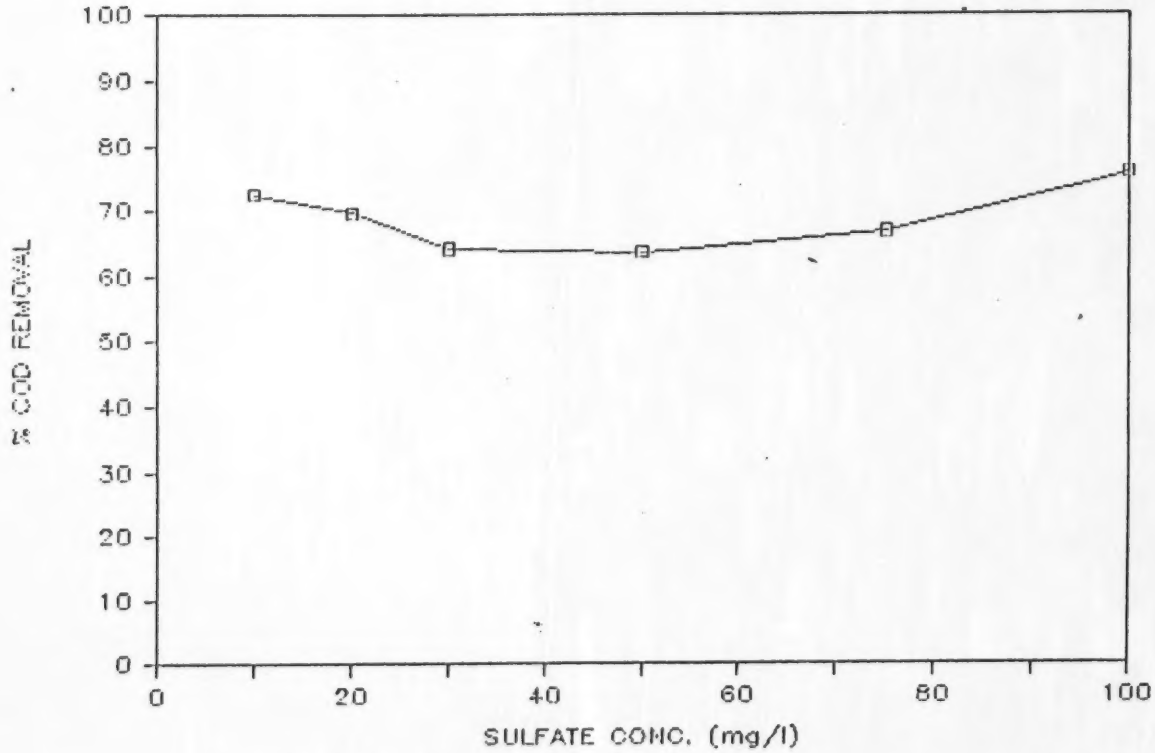

FIGURE 13. % COD Removal Versus Sulfate Concentration for the Laboratory Scale Reactors

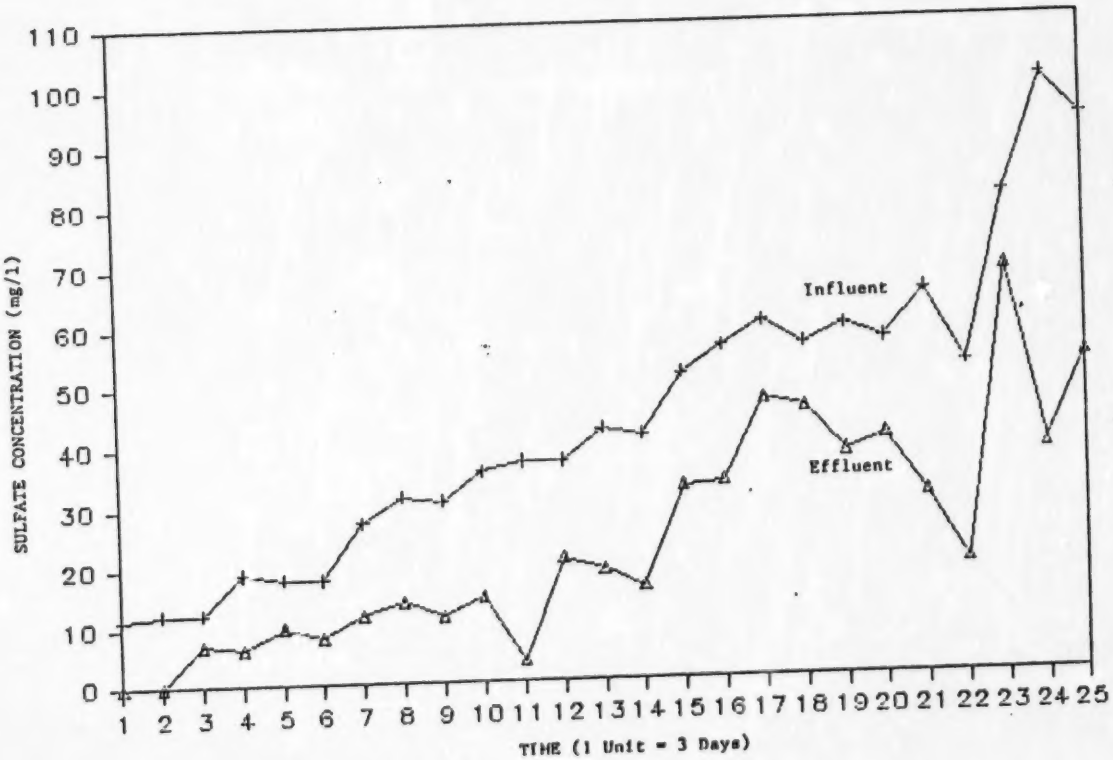

FIGURE 14. Sulfate Concentrations in Laboratory Reactors

CONCLUSIONS

In pilot scale experiments total COD removals up to 75% were obtained, although average removals for the three systems investigated were somewhat less. However, this performance may not be representative of the anaerobic expanded bed contactors. It is believed that the presence of sulfate reducing bacteria adversely affected methanogenesis. Consistently better results were obtained in the laboratory scale experiments conducted with synthetic wastewater which did not contain excess sulfate. The level of sulfate to COD ratio which adversely effects the anaerobic process is being investigated.

The reactors were operated in continuous flow stirred tank reactor mode and the results are reported in COD. Higher removal efficiencies are expected in plug flow reactor mode or continuous flow stirred tank reactors in series. Reporting the data in BOD would also result in BOD removal efficiencies which will be higher than the COD removal efficiencies reported in this paper.

In the early part of the research plugging problems occurred in the graded gravel underdrains. Design of systems which will not plug will be a major challenge for designers of full-scale reactors.

When methane production occurred the methane bubbles attached to and floated the sand media to the surface of the reactor. It will problably be necessary to install equipment to break up the bubble/media mass.

In a newly developed process it is difficult to separate the process performance from the system performance. In the laboratory set-up it was observed that any disturbance in the system such as changing feeder pipes etc., adversely affected the performance of the system. In order to minimize these disturbances the reactors were modified several times resulting in a more stable operation. As the design of the reactors improves the anaerobic expanded-bed system may prove to be a viable alternative for treating municipal sewage.

ACKNOWLEDGEMENTS

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DISCLAIMER

Although the research described in this article was conducted by the United States Environmental Protection Agency under its inhouse research program, it has not been subjected to the Agency's peer and administrative review and, therefore, does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

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